VOL. V. No. 2.

# JOURNAL

OF

# THE ENGINEERING SOCIETY

OF

## THE LEHIGH UNIVERSITY.

ISSUED QUARTERLY.

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FEBRUARY, 1890.

# JOURNAL

OF

# THE ENGINEERING SOCIETY.

ISSUED QUARTERLY.

Subscription, $1.00 per Year. Single Copies, 25 Cents.

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[*Entered at the Post Office at Bethlehem, Pa., for transmission through the mails at second-class rates.*]




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DAILY TIMES PRINT,
BETHLEHEM, PA.

JOURNAL

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VOL. 5. FEBRUARY, 1890. NO. 2.

# A NEW FORM OF GAS PRODUCER.

It is a well known fact that in ordinary furnaces, where substances are heated by contact with the gaseous products of combustion, a considerable portion of the heat developed in the fire place is carried out by these gases as they issue from the furnace. The conditions of the process carried on in the furnace impose limits to the variations admissible in the temperature of the escaping gases. When very high temperatures are required the loss of heat due to this cause becomes enormous. This explains the great saving of fuel which was effected by the introduction of the Siemens regenerative gas furnace for processes requiring the production and maintenance of very high temperatures. This furnace may be said to have revolutionized some branches of metallurgy. One process, notably, in iron metallurgy, the open hearth or Siemens-Martin process, became practicable only after the adoption of the Siemens furnace. The principle of this furnace, as is well known, is the interception of the heat carried out by the waste gases and its restoration to the process or, to use the technical expression, its regeneration by transferring it to the air and fuel which are supplied to the furnace. The transference is effected by causing the gases to pass down through so-called regenerators, *i.e.*, chambers filled with a chequer work of fire brick to which they impart the greater portion of their heat, and then, by reversing valves suitably arranged, caus-

ing a current of gaseous fuel and one of air for its combustion to pass up through these regenerators, and thus to take up and carry back to the furnace the greater part of the heat which had been deposited in them by the previous current of waste gases. A regenerator in its ordinary form may be considered as a mass of masonry, the top of which is constantly at a bright red to a white heat, while the base is constantly at a comparatively low temperature, varying let us say, from 150° to 250° C. Between these extremes the temperature in the intermediate portions of the regenerator varies, but not at a constantate. When the heating current is turned off and the upward, cooling current has just been admitted, the region of very high temperature extends nearly to the base. The action of the cooling current diminishes the extent of this region and its lower limit gradually recedes until it almost reaches the top of the regenerator. Then the currents are reversed and under the action of the downward, heating current, the limit of the region of very high temperature creeps slowly down again nearly to the base, until its progress is arrested by a fresh reversal of the valves. This method of working accounts for the fact that the mean temperature of the mass of brickwork in the regenerator may be raised or lowered to a considerable extent while the temperature of the gas issuing at either end varies but slightly. This efficiency of regeneration is the great merit of the Siemens furnace, and has masked the defects inherent in the system, as originally designed.

An arrangement which was adopted by Siemens in connection with his furnace was to separate the gas producers entirely from the furnaces and to convey the gas from the former to the latter through a long tube which he called the cooling tube. The chief object of this was to prevent the clogging of the valves and the obstruction of the passages in the regenerators by the tar and soot deposited by the gas.

It is clear that this cooling of the gas involves a serious loss of heat. Not only is the fuel in the shape of the condensed tar and soot lost to the process, but a considerable part of the heat developed in the producer is carried out by the producer gas in the form of sensible heat, and is lost if this gas is cooled before it enters the furnace. Taking the simplest case of the conversion of fixed carbon into carbonic oxide by atmospheric oxygen, it

can be demonstrated that about thirty per cent of the heat which can be developed by the complete combustion of carbon is developed by the reaction within the producer, and can escape therefrom only by transmission through the walls, the grate, etc., or in the hot coke and ashes raked out below, or finally in the issuing gas. In well constructed and well managed producers the escape of heat through the causes first mentioned is comparatively small, so that by far the greater part of the heat developed in the producer must be found as sensible heat in the issuing gas. (It must be borne in mind that the simple conversion of fixed carbon into carbonic oxide is assumed to be the only reaction in the producer.) If the greater portion of this heat is abstracted before the gas enters the furnace, it is clear that a considerable proportion of the total calorific power of the carbon employed to generate the gas must thereby be wasted.

The actual use of the cooling tube in practice was not found to involve a greater consumption of fuel, when compared with the practice of building the producer close to the furnace, to the extent which the foregoing considerations would lead us to expect.

The reason of this apparent anomaly becomes clear when we consider what has just been said with regard to the conditions of the efficient operation of the regenerator. These conditions require that the base of the regenerator shall be kept constantly cool, so that the gases escaping therefrom shall have no higher temperature than is needed for the draught of the chimney; but this part of the regenerator is where the gas from the producer enters. The introduction of hot gas at this point heats chiefly that region of the regenerator which the conditions of efficiency require to be kept constantly at a low temperature and thus impedes its efficient action. In other words, the larger part of the heat brought into the regenerator by the producer gas, being stored in its cooler region, is swept out of it again by the current of issuing gases after the next reversal, and increases the quantity of heat escaping through the chimney. If Siemens' original method of regeneration is employed, there is no advantage in taking the gases hot from the producer to the regenerator, and the lowering of their temperature in the cooling tube does not occasion an avoidable waste of fuel. The statement just made, however, does not involve the denial of the existence of such a loss. On the contrary, it is beyond question that such a loss exists. I have stated that this loss, in the case of the conversion of fixed carbon

into gas by partial combustion in air, constitutes about thirty per cent. of the total calorific power of the fuel charged into the producer. In the case of fuels containing volatile elements the calculation is not so simple, and its results will vary with the proportion and the nature of the volatile elements, but in all cases where a fuel of high calorific power is charged into the producer, the loss occasioned by the cooling of the producer gas is considerable, and its ratio to the calorific power of the fuel is not much inferior to that determined for fixed carbon. In case tar and soot are deposited by the cooling gas, there is a further loss due to the abstraction of fuel in these forms from the furnace.

Various attempts have been made to prevent this loss. The idea was suggested, to do away with one of the regenerators at each end of the furnace, to put the producer close to the furnace, and to use the regenerative principle only for the heating of the air required for combustion in the furnace. This was not found to be productive of the anticipated economy. The reason is obvious. The efficiency of regeneration depending on the existence of a region of constantly low temperature at the base of a regenerator, requires that the calorific capacity of the cooling current shall be nearly equal to that of the heating current. As the calorific capacity of the weight of air theoretically required for the complete combustion of the producer gas is not quite one half of that of the products of combustion issuing from the furnace, it is evident that the current of air in rising through the regenerator, can not take up as much heat as has been imparted to the regenerator in an equal time by the current of waste gases from the furnace, unless the range in the temperature of the latter current is much less than that of the former. This is equivalent to saying that the waste gases must escape at a considerably higher temperature than that of the external air, or that the heat which they carry from the furnace is imperfectly intercepted.

Some inventors have abandoned the regenerator, and heat the air for combustion in the furnace by causing it to pass through what is termed a recuperator. In this there is a steady and continual current of air in one direction, and one, also continual, in the opposite direction, of the waste gases from the furnace. The two currents are separated by partitions constructed of retractory tiles, tubes or bricks. This device does not overcome the difficulty. The inequality in the calorific capacities of the two currents, pointed out as the cause of imperfect interception of

the waste heat of the furnace in the previous case, still exists in this arrangement and produces the same effect. In the recuperator there is an additional reason for the higher temperature of the heating than of the cooling current. In order that heat shall be transmitted with sufficient rapidity through the partition, which must be constructed of a material which is a bad conductor of heat, there must be a considerable difference in the temperature of the currents in contact with its opposite sides. The substitution of recuperators for regenerators has resulted in some cases in a slight economy of fuel. This indicates only that in those cases the saving effected by the introduction of the fuel gas hot from the producer was slightly in excess of the loss suffered by the imperfect interception of the heat of the waste gases of combustion.

In my lectures on Metallurgy at this University, I have for a number of years pointed out this difficulty, and suggested that it could be almost completely remedied by employing the regenerators to heat, not only the air for the furnace, but also that required for the producer, taking the gas hot from the latter to the furnace. Thus the calorific capacity of the cooling current could be made nearly equal to that of the heating current. An additional advantage of this arrangement is that it would tend to fulfill one of the conditions for the efficient working of the producer, namely, the maintenance of a high temperature within it.

Another method of avoiding this loss of heat, is to utilize the excess of heat developed in the producer by causing it to perform some useful work in the producer itself. This has been successfully accomplished in the case of fuels of inferior quality from the large proportion of moisture which they contain. A notable example of this is the employment of damp saw dust and peat in Sweden in the manufacture of fuel gas, which is used for the production of very high temperatures. The vapor of water expelled from the fuel is removed from the gas by condensation. For this purpose the gas is brought into so-called Lundin condensers, where jets of cold water reduce its temperature to such a point as to effect the nearly complete condensation of the moisture which it carries. The gas, thus purified, is as efficient as that produced from the best fuel. Of course the gas issues from the condenser at a lower temperature, than that which flows from Siemens' cooling tube, so that at first glance, it might seem that

the loss of heat must be even greater. This is not the case, however, because almost all of the heat developed in the producer is utilized within it in the expulsion of moisture from the fuel. This is effected by increasing the size of the producer, and thus providing a region in which the gas issuing from the lower or gas-making region may be employed in heating and drying the fresh charges of fuel. The temperature of the gas is thus reduced, so that it issues from the producer at a temperature not far from the boiling point of water, and the loss of heat in the condenser is thus rendered comparatively small.

Another device for accomplishing the same result, is the utilization of the excess of heat developed in the producer for the production of water gas, by the reaction of steam on carbon producing hydrogen and carbonic oxide, as expressed by the equation

$$H_2O + C = 2H + CO.$$

Thus the sensible heat of the producer gas may be converted into potential heat, which in the furnace is again converted into sensible heat. The method of accomplishing this is simple, and consists in allowing steam to pass into the producer with the air which enters through the grate. In some cases, this is stated to have effected a certain saving of fuel. It is, however, a dangerous remedy, which can easily be abused. The reaction involved in the production of water gas, absorbing heat, tends to chill the producer, and thus contravenes one of the requirements for its efficient operation, namely, the maintenance of a high temperature within the region where the reactions should occur. There is a difference between this case and the preceding. In the saw dust producer the temperature of the gas is lowered in its upper region, but by increasing the dimensions of the producer, and thus affording space for the drying and heating of the fuel before it reaches the gas-making region, the temperature of the latter may be kept from sinking below the desired point.

On the other hand, when water gas is made in the producer, the chilling effect is produced in the gas-making region itself and its evil results are shown by the increase in the proportion of carbonic anhydride in the issuing gas, which is invariably found when steam is admitted into the producer, and which is the greater the more steam is admitted. The carbonic anhydride in the escaping gas is always accompanied by steam, which has also escaped decomposition, but which usually does not appear

in the results of analysis, because that is performed on the dried gas. The decomposition of $H_2O$ or $CO_2$ by carbon requires a sufficient surface of carbon and a high temperature, a bright red heat. A lowering of the temperature in the gas-making region of the producer, is likely to result, therefore, in the escape from the producer of a portion of these gases undecomposed. The presence of these gases simply adds to the proportion of inert constituents of the gaseous mixture issuing from the producer. The evil effects of these inert gases are a diminution of the inflammability of the mixture, a lowering of the temperature of combustion and an increase of loss, due to the heat escaping through the chimney. In the case of carbonic anhydride, we have also the escape of some of the carbon of the fuel, which might have been utilized to produce heat in the furnace by combination with oxygen, but which, having already taken up as much oxygen as it can combine with, is no longer available as a fuel. It is true that the Siemens system of regeneration mitigates to a great degree all of the evil effects of the presence of inert constituents in the producer gas, but they are not entirely removed, especially the last or the amount of heat carried off by the gases escaping through the chimney.

Still another method of overcoming the difficulty has been recently proposed in the new form of gas producer, to which I desire to call attention in this paper. It has been developed by two members of the technical staff of Mr. Frederick Siemens, and has been described in a paper read before the Iron and Steel Institute at its recent meeting in Paris.* In this new modification of Siemens' system the gas regenerators are dispensed with and that portion of the waste gases from the furnace which would have passed through them, is delivered under the grate of the producer and forced to pass through the mass of fuel upon it. These gases consist essentially of $N$ and $CO_2$ with more or less $H_2O$. In some cases they also contain air which has been admitted to the furnace in excess. In others they may contain an excess of gaseous fuel. For the sake of simplicity we will assume for the present that they contain only nitrogen and carbonic anhydride in the proportions which would result from the combustion of fixed carbon in air. The nitrogen suffers no chemical change but the carbonic anhydride in con-

*Journal of the Iron and Steel Institute, No. II., 1889, p. 256.

tact with the incandescent carbon in the producer is reduced to carbonic oxide. We have here a reaction precisely similar to that involved in the production of water gas, as will appear from the following equations expressing them:

$$CO_2 + C = CO + CO.$$
$$H_2O + C = 2H + CO.$$

In each of these reactions one molecule of incombustible gas is converted into two molecules of combustible gas, taking up one atom of carbon. The thermal results of the two reactions are not very unlike. The heat absorbed in the reaction between gaseous steam and carbon is 2347 calories per unit of carbon. The heat absorbed in the reduction of carbonic anhydride by carbon is 3134 calories per unit of carbon. These are hypothetical results, being based upon the assumption that the reactions take place at $0° C$. It has been demonstrated that a temperature of about $900° C$ is required in order that active decomposition of steam or carbonic anhydride by carbon may ensue. The quantities of heat absorbed at $900° C$ in the reduction of $H_2O$ and $CO_2$ by the unit of weight of carbon are 2424 and 3147 calories respectively. The excess of heat required to decompose the $CO_2$ is counter-balanced by the higher calorific power of the products of its decomposition, and will therefore be recovered when these products are burned. The calorific powers of the products of the reaction of a unit of weight of carbon with $H_2O$ and $CO_2$ respectively are 10088 calories and 10811 calories, assuming that the combustion takes place at $900° C$.

There are essential differences, however, between the new proposal, and the method of utilizing in the production of water gas the excess of heat developed in the producer. The sources and the quantities of heat are different. By the new method it is the waste heat from the furnace, not that of the producer, which is utilized and, the quantity being much greater, the heat absorbing reaction, which by the old method is subordinate (the chief reaction remaining the conversion of $C$ to $CO$ by oxygen of the air,) becomes in the new method predominant. In other words, instead of converting carbon into carbonic oxide, chiefly by atmospheric oxygen, the inventors propose to effect the conversion by $CO_2$, and to supply both the $CO_2$ and the heat necessary for the reaction from the waste gases of the furnace. The question arises, is the heat thus supplied sufficient for the complete decomposition of the $CO_2$?

If we were able to control at our pleasure the distribution of the heat, and if the temperature in the furnace could be caused or allowed to rise indefinitely, we could at once reply in the affirmative. Of two molecules of carbonic oxide entering the furnace the heat developed by the combustion of one would suffice for the decomposition of a molecule of $CO_2$ in the producer into $CO$ and $O$, thus leaving us free to utilize the heat developed in the producer by the combination of an atom of carbon with the oxygen thus set free, and the heat developed in the furnace by the combustion of the molecule of $CO$ thus formed. By this arrangement there would be no losses of heat, beyond those due to transmission through the walls of producer, furnace and regenerators, and the small amount escaping to the chimney with the gases leaving the regenerator. As a molecule of oxygen would pass up through the regenerators for every molecule of $CO_2$ passing down through them, and each molecule of oxygen would be accompanied by the same number of molecules of nitrogen as would accompany a molecule of $CO_2$ the calorific capacity of the ascending and descending currents would be nearly equal, and the chimney loss could thus be kept from rising much beyond the usual limit with Siemens' ordinary system of regeneration. The postulates we have made are, however, conspicuously inexact. We cannot dispose at our pleasure of the heat developed in the producer and in the furnace, and the temperature cannot be increased indefinitely. Dissociation imposes a limit to the rise in temperature, and, moreover, the quantity of heat lost by transmission through the walls of the furnace and the regenerators increases rapidly as the temperature rises. In fact the quantity of heat thus abstracted is purposely increased to prevent the destruction of the more exposed portions of the furnace.

A more practical way of solving the problem is to estimate the quantity of heat which the waste gases of the furnace can furnish when their temperature sinks between the limits which the chemical and physical conditions of the process in practice impose. I know of no determination of the temperature of the gases escaping into the regenerators of a Siemens furnace, but considering the more recent determinations of the temperatures of fusion of refractory metals, I think it unlikely that in current practice the temperature of the gases delivered to the producer

would exceed 1500° *C*. For lack of more certain information we can assume this as our upper limit. As I have stated, it has been found that for active decomposition of $CO_2$ by carbon, a temperature of at least 900° *C* is required. This temperature can therefore be taken as the lower limit to the range of temperature which can be utilized for the conversion of the sensible heat of of the waste gases into potential heat in the producer. Upon the assumption which we have made that the products of combustion consist only of nitrogen and carbonic anhydride we can readily determine their calorific capacity. We will take as before the unit of weight of carbon as our standard.

The calorific capacity of a quantity of waste gases containing 1 kil. of carbon is

| | | |
|---|---|---|
| 3.67 kil. of $CO_2$ | $3.67 \times 0.216$ | 0.796 |
| 8.89 kil. of $N$ | $8.89 \times 0.244$ | 2.169 |
| | | 2.965 |

The range of temperature we have assumed is 1500—900= 600. $2.965 \times 600 = 1779$ calories. We have found however that the heat absorbed by the reaction of 1 kilogram of carbon on $CO_2$ is 3147 calories. The heat therefore which the waste gases can yield to the producer suffices for the reduction of somewhat less than 60 per cent of the $CO_2$ which they contain.

There are two ways in which this difficulty may met. We may, in the first place, supply the heat necessary for the conversion of the remainder of the carbonic anhydride to carbonic oxide by admitting air to the producer, and thus effecting the partial combustion of some of the carbon to carbonic oxide by means of atmospheric oxygen, a reaction which develops heat. The deficiency to be supplied being 3147—1779 or 1368 calories, and the calorific power of carbon forming carbonic oxide being 2473 calories, if the reduction of $CO_2$ must be complete, for every kilogram of *C* passing into the producer gas by this reaction, 0.55 kilogram of carbon must be burned to *CO* by air admitted to the producer. If the waste gases contain free oxygen, this of course could be utilized, and the quantity of heat it would supply would be increased by the sensible heat which it and the nitrogen accompanying it could yield. The proportion of air in excess admissible in the gases of the furnace is determined by other considerations than the saving of heat in the producer, and it is those considerations which would decide how far the air

needed in the producer could be supplied in the furnace there to absorb heat for transmission to the producer. The presence of the excess of air in the furnace would be accompanied by all the evils involved in the presence of inert gases therein, notably by an increase in the chimney loss. On the assumption, however, that only $N$ and $CO_2$ exist in the waste gases, and all the air to be supplied to the producer comes directly from the external atmosphere, would there be an increase in the chimney loss? In the decision of this question it is important to remember that in any permanent régime the weight of the waste gases evacuated in a certain number of hours must be equal to the weight of fuel gasified in the producer, in addition to the weight of air and steam admitted to both producer and furnace in the same period As only the air admitted to the furnace passes up through the regenerator, and as this constitutes under the assumed condition but 82 per cent of the total quantity of air admitted to the system, the rest entering the producer, it is clear that the calorific capacity of the ascending current in a regenerator will no longer be nearly equal to that of the descending current, and the chimney loss will be increased. Its increase, of course, will not be nearly so great as when the gas regenerators are dispensed with, and all the carbonic oxide generated in the producer from fixed carbon is obtained by partial combustion with atmospheric oxygen, but the efficiency of the regenerators will be somewhat impaired.

The other method of meeting the difficulty is to content ourselves with the partial decomposition of the $CO_2$ of the waste gases, and to gasify a sufficient weight of carbon in the producer by increasing the quantity of gases we cause to enter it. By this method, instead of admitting 3.67 kil. $CO_2$ and 8.89 kil. $N$ for every kilogram of carbon gasified we would admit 6.5 kil. $CO_2$ and 15.7 kil. $N$, and the producer gas would consist of

4.67 kil. $CO$ = 20 per cent.
2.83 kil. $CO_2$ = 12 per cent.
15.70 kil. $N$ = 68 per cent.

We would admit to the furnace 2.67 kil. $O$ and 8.89 kil. $N$, thus producing 10.17 kil. $CO_2$ and 24.59 kil. $N$, of which 6.5 kil. $CO_2$ and 15.7 kil. $N$ would be returned to the producer, leaving 3.67 kil. $CO_2$ and 8.89 kil. $N$ to pass down through the regenerator and thence be evacuated through the chimney. The excess of inert gas in this case would not be accompanied by an increase

in the chimney loss, as it would not pass off through the chimney, but it would exert whatever other ill effects such inert gases occasion, such as a diminution of the inflammability of the gas and of its temperature of combustion, especially as the producer gas would enter the furnace at a temperature below 900° instead of 1300°—1500°, as in the case of the ordinary Siemens furnace. It is possible that with such a proportion of inert constituents the temperature of 1500°, assumed as that of the gases reaching the producer, could not be maintained, in which case a still greater quantity of inert gas would be needed, and thus the evil would be intensified. How far it is practicable to go in this directicn in any case can only be determined by experiment.

These considerations enable us to detect the fallacy of the claim made in the paper to which I have referred, that this method will save one half of the fixed carbon gasified in an ordinary producer. It is quite true that to produce a given weight of $CO$ by reaction between $CO_2$ and $C$ only one half of the weight of carbon is taken up that is needed for the production of the same weight of $CO$ by the partial combustion of carbon with oxygen, but the $CO$ produced in the former case will be accompanied by a larger proportion of inert gases, and will be delivered to the furnace at a much lower temperature than in the latter case. To produce the same effect in the furnace a larger quantity of $CO$ will be needed in the former case than in the latter.

In the foregoing calculations I have not taken into consideration the fact that the inventors draw the waste gases from the furnace and force them through the producer by means of a steam jet, so that steam passes into the producer with the waste gases, and also becomes a constituent of these gases by the combustion in the furnace of the hydrogen resulting from its decomposition in the producer. From the comparison we have made between the quantities of heat involved in the decomposition of $CO_2$ and $H_2O$ respectively, we can estimate what the result of the admission of steam in each of these ways will be. One kilogram of carbon in reaction with steam in the producer sets free 0.167 kil. H. This weight of hydrogen burning in the furnace gives rise to the following constituents of the waste gases, viz.:

| | |
|---|---|
| $H_2O$. | 1.50 kil. |
| $N$. | 4.44 kil. |

The calorific capacity of these gases is thus computed,

$$H_2O. \quad 1.50 \times 0.4805 = 0.721$$
$$N. \quad 4.44 \times 0.244 = 1.084$$
$$\overline{\quad 1.805 \quad}$$

In cooling from 1500° $C$ to 900° $C$ these gases will yield $1.805 \times 600 = 1083$ calories.

It thus appears that the steam in the waste gases, involving the presence of only half as much nitrogen as the $CO_2$ carries with it, would yield but 1083 calories to the producer per unit of carbon taken up. Its decomposition would absorb 2425 calories, as we have found. The heat to be supplied is therefore 1341 calories, almost identical with the quantity of heat needed for the corresponding reaction with the $CO_2$ of the waste gases. With the steam of the jet the case is different, as this is not accompanied by nitrogen, and it enters the producer at a temperature much below that required for its decomposition. The amount of heat to be supplied in this case is $2424-(0.721 \times 150) = 2424-110 = 2314$ calories, considerably more than that required for the reaction with the $CO_2$ of the waste gases. There is some compensation, however, in the fact that, bringing with it no nitrogen, it tends to diminish the proportion of inert constituents in the producer gas.

In conclusion we may infer from the foregoing considerations, that, while the proposed modification of the Siemens system does not present a complete solution of the problem of attaining the greatest possible economy in the use of gaseous fuel, it constitutes an important step in advance, and the introduction of the new form of producer should be accompanied by a considerable saving in fuel. In the paper quoted the statement is made that it has been successfully worked in practice, but the comparison there made is between this modification of the Siemens furnace and an ordinary furnace burning solid fuel. Further advantages claimed for it with apparent reason are its simplicity and the lower cost of its construction than that of an ordinary Siemens furnace with producers, owing to the suppression of one pair of regenerators. This process is similar in principle to Ehrenwerth's process, proposed several years ago, for the increase of the efficiency of the waste gases from a blast furnace. The novelty of the present process consists in the application of this principle to the Siemens furnace.

BENJ. W. FRAZIER.

# FUEL-GAS.

## RESUME OF THE RESULTS OBTAINED IN THE GENERATION OF WATER-GAS AND PRODUCER-GAS IN THE SAME VESSEL.

In a previous paper I gave the results of an unsuccessful attempt to solve the "fuel-gas problem" by manufacturing a gas which was composed of the three commercial gases,—coal, water and producer.

After this failure it was decided to conduct a series of experiments in one producer, in which both water-gas and producer-gas should be generated *from bituminous coal.* All commercial water-gas had, previous to this time, been manufactured from either anthracite or hard coke, and for this reason the results of this undertaking were awaited with much interest.

The producer which was used in these experiments was one which had been used for generating water-gas in the previous investigations. The remainder of the apparatus was the same as was used previous to this, and, in fact, closely resembled that of any water-gas plant, with some economic modifications for utilizing waste heat.

The *modus operandi* was as follows: After the fire in the producer had attained a sufficient height (usually about eight above the grate-bars) the blower was stopped, and by means of a small valve sufficient air was admitted to make about three hundred feet of producer-gas per minute, this being the capacity of the station meter. This operation was continued usually for five minutes, when all air was turned off and steam admitted at the bottom of the producer. It was found that at the end of five minutes the fire would become so chilled that the heat was not sufficient to decompose the steam readily, and the production of water-gas was stopped in order to increase the heat by the blowing apparatus. This operation also required about five minutes, so that gas was being generated for two-thirds of the time, whereas in making water-gas alone half of the time was consumed in blowing. At the end of five minutes the generation of producer-gas would again take place, and the whole process repeated in the same way during the day.

During the blast the waste gas was conducted through an underground flue to the combustion chamber of the boiler, thus utilizing all of the hydro-carbons given off by the coal.

The following table shows the results obtained by this method from Youghiougheny gas coal during a continuous run of one hundred and thirty-eight hours:

| 1888. | Gas Made. Cubic Feet. | Coal Charged Pounds. | Yield of Gas per pound of Coal Charged. | Yield of Gas per ton of Coal Charged. | Used at Boiler | | Refuse. | | Per Cent of refuse to Coal charged |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Coal Lbs. | Ref'se Coke Lbs. | Coal Lbs. | Coke Lbs. | |
| Sept. 5 | 395,000 | 15,000 | 26.3 | 52,600 | | 2205 | 1283 | 876 | 8. |
| " 6 | 456,000 | 13,500 | 33.7 | 67,400 | 750 | 2024 | 1088 | 876 | 8. |
| " 7 | 413,000 | 11,750 | 35.2 | 70,400 | 894 | 1426 | 1426 | 894 | 12. |
| " 8 | 409,000 | 14,250 | 28.7 | 57,400 | 897 | 1128 | 1128 | 744 | 7.9 |
| " 9 | 470,000 | 12,500 | 37.6 | 75,200 | 533 | 1580 | 1580 | 533 | 12.5 |
| " 10 | 316,000 | 10,700 | 29.5 | 59,000 | 271 | 1279 | 1279 | 627 | 11.9 |
| Total, | 2,459,000 | 77,700 | 31.6 | 63,200 | 3345 | 9642 | 7784 | 4550 | 10.1 |

The quality of the gas made on the different days may be seen from the following volumetric analyses:

ANALYSIS OF A MIXTURE OF WATER AND PRODUCER GAS.

| SEPTEMBER | $CO_2$ | $O$ | $C_2H_4$ | $CO$ | $CH_4$ | $H$ | Percentage of Combustibles |
|---|---|---|---|---|---|---|---|
| 4 to 5 | 5.71 | 0.10 | 0.41 | 25.61 | 3.21 | 29.65 | 58.88 |
| 5 to 6 | 6.70 | 0.17 | 0.73 | 23.55 | 4.63 | 29.40 | 58.33 |
| 6 to 7 | 5.03 | 0.08 | 0.58 | 26.58 | 4.21 | 30.38 | 61.98 |
| 7 to 8 | 6.50 | 0.27 | 0.45 | 24.14 | 3.53 | 30.42 | 58.54 |
| 8 to 9 | 5.30 | 0.12 | 0.70 | 23.73 | 4.09 | 31.61 | 60.13 |
| 9 to 10 | 6.50 | 0.13 | 0.80 | 23.03 | 3.65 | 30.05 | 57.53 |
| Average, | 5.87 | 0.15 | 0.61 | 24.44 | 3.89 | 30.26 | 59.20 |

An analysis of the waste gas, given off during the blast was as follows:

Analysis of waste gas:

| | |
|---|---|
| Carbonic acid ($CO_2$) | 9.70 |
| Oxygen ($O$) | 0.63 |
| Olefiant gas ($C_2H_4$) | 0.10 |
| Carbonic monoxide ($CO$) | 10.10 |
| Marsh gas ($CH_4$) | 2.10 |
| Hydrogen ($H$) | 7.99 |
| Percent. of combustibles | 20.20 |

This waste gas contained such a small percentage of combustibles that it would not burn unaided, and together with the fact that there was present such a large percentage of nitrogen and carbonic acid, it was doubtful economy, in the opinion of the writer, to pass this gas over the coal fire under the boiler.

The mixture of the two gases contained eleven millions eight hundred thousand (11,800,000) heat units per ton of coal, so that it represented on efficiency of about forty-seven (47) percent of the theoretic energy of the coal.

This gas, unpurified, was manufactured at a cost of about six cents per thousand feet in the holder at the works. In its manufacture, if it were to be successful, there were several difficulties to overcome; first, there was a considerable amount of sulphurretted hydrogen ($H_2S$) in the gas, which must have been removed, before it could have been adopted for domestic consumption. This would have necessitated the construction of purifying houses, and to the cost of the gas would have been added, the cost of purification, which would, however, have been nominal by the use of the oxide of iron; second, the gas contained a large amount of liquid hydro-carbons in suspension, which must have been removed; otherwise the gas mains would have very soon become useless; third, the percentage of combustibles in the gas was not large enough to give sufficient heat for ordinary culinary purposes. There could have been only one way of overcoming this objection, viz.: by diminishing the proportion of producer gas, and this reduction would have so decreased the yield per ton of coal, that the cost of manufacture would have been too high.

Various modifications were made in the producer from time to time, looking toward a larger yield of gas per ton of coal consumed, and also with a view to saving a considerable part of the combustibles previously given off during the blast. By referring to the analysis of the waste gas given above, it is seen that it contains more than two per cent by volume of marsh gas. Since the volume of waste gas is many times that of the gas made, this percentage represents an enormous loss of energy.

The producer, being fourteen feet in height, has at its different depths, coal in various stages of distillation until the bottom is reached, when on observation, it is found that the coal has been converted into coke, not such a variety as is made for metallurgical purposes, but which consists of a black spongy mass. It is in this lower part of the producer that the larger part of the water gas is generated.

To save the marsh gas given off during the blast, it was decided to build a circular flue in the brick lining of the producer, and have port holes leading from the fire at different

points, to this flue, which was built about five feet above the grate bars, and through which the waste gases would be carried off during the blast. In this way, there was about three or four feet of fire above the ports, and it was thought, and afterwards proved, that the hydro-carbons would be given off during the time required for the coal to pass from the top of the fire down to the ports. As before the gases were taken off at the top of the generator.

At the same time, the pipe through which the steam entered the producer was arranged differently. Heretofore, as in nearly all water gas generators, the steam was admitted through one pipe at the bottom. In place of this, the pipe was arranged in a circle, and six entrance pipes were conducted from it to the inside of the producer.

There was considerable difficulty encountered in working the fire, owing to the tendency of the coal in coking, to arch over and hang to the sides of the vessel. This was finally overcome by constructing a rammer inside of the producer, which was operated by compressed air, and which also kept the fire compact, so that the gases could not escape in crevices. To save time and the gases which were previous to this time, lost during the process of charging the coal, a hopper was constructed, which could be operated during the period of gas making.

The following experiments were made with the producer in its improved state with Ohio coal. No fair comparison can be made between these tests and those of the Youghiogheny coal, since the latter is of much better quality.

The following analysis of the coal with which these tests were made is here given.

ANALYSIS OF OHIO COAL.

| | |
|---|---|
| Moisture, | 3.22 |
| Volatile Matter, | 57.61 |
| Fixed Carbon, | 34.54 |
| Ash, | 4.63 |
| Sulphur, | 2.84 |

Result of an experiment with above coal during a continuous run of twenty-four hours.

| | |
|---|---|
| Gas made, (temperature 94° Fah.) | 407,900 cubic feet. |
| Gas made, (temperature 60° Fah.) | 383,426 cubic feet. |

| | |
|---|---|
| Coal charged, | 15,325 pounds. |
| Refuse, | 1,833 pounds. |
| Percentage of refuse, | 11.3 pounds. |
| Yield of gas at 60° Fahr., per pound of fuel, | 25 cubic feet. |
| Yield of gas, | 50,000 cubic feet. |

The gas gave the following analysis. In order to show the difference by weight and volume, both are here given.

ANALYSIS OF GASES:

| | BY VOLUME. | BY WEIGHT. |
|---|---|---|
| Carbonic acid, ($CO_2$) | 10.50 | 24.44 |
| Oxygen, ($O$) | 0.25 | 0.43 |
| Olefiant gas, ($C_2H_4$) | 0.65 | 0.97 |
| Carbonic monoxide, ($CO$) | 21.70 | 31.99 |
| Marsh gas, ($CH_4$) | 3.30 | 2.77 |
| Hydrogen, ($H$) | 39.85 | 4.20 |
| Nitrogen, ($N$) | 23.75 | 35.20 |
| | 100. | 100. |

Another test with the same coal gave the following results:

| | |
|---|---|
| Gas made, (temperature 93° Fahr.) | 410,700 cubic feet. |
| " " " 60° Fahr.) | 386,100 " " |
| Coal charged, | 15,400 pounds. |
| Refuse, | 2,522 " |
| Percentage of refuse, | 15.8 |
| Yield of gas, per pound of fuel charged, | 25,18 cubic feet. |
| " " ton " " | 50,360 " " |

The quality of the gas may be judged from the following analysis:

ANALYSIS OF GAS:

| | BY VOLUME. | BY WEIGHT. |
|---|---|---|
| Carbonic Acid, ($CO_2$) | 8.9 | 20.48 |
| Oxygen, ($O$) | | |
| Olefiant gas, ($C_2H_4$) | 1.0 | 1.48 |
| Carbonic monoxide, ($CO$) | 22.0 | 32.02 |
| Marsh gas, ($CH_4$) | 3.2 | 2.66 |
| Hydrogen, ($H$) | 38.0 | 3.96 |
| Nitrogen, ($N$) | 26.9 | 39.60 |
| | 100. | 100. |

This gas contained 64.2 per cent. of combustibles by volume, and yielded 12,555,000 heat units per ton of coal consumed. This would represent an efficiency of over fifty per cent.

In all these results, showing the yield of gas per ton of coal used, no account is taken of the coal consumed at the boiler, so that they are manifestly too high.

While the results of this series of experiments appear on the surface to be very promising they will not enable a company to compete with coal for fuel purposes. An ordinary gas stove with an efficiency of ninety-five per cent. consumed twenty-four hundred feet of gas, which contained at least fifty per cent of combustibles, in an experiment conducted during one of the above tests, without raising the temperature of a room ten feet square above 75° Fah. This gas could not be sold for less than fifteen cents per thousand feet, so that to operate the gas stove above it would cost more than thirty-five cents per day, or say ten dollars per month. This would most assuredly place it beyond the reach of the average family in any of our cities. Of course, if we wish to take the same ground with regard to gas for fuel purposes that we take with electricity for illumination, it might be made a paying investment, but considered strictly from an economic standpoint there is to-day, in the writer's opinion, no coal fuel-gas process which can compete with coal for domestic use.

J. F. MERKLE, C. E., '84.

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## THE HOLBROOK SPIRAL AS A TRANSITION CURVE.

A transition curve in railroad alignment is a curve used to ease off changes in curvature. While the theoretic necessity of such curves is very generally recognized, the practical application of them is almost as generally neglected by the engineer corps, both in location and in maintenance of way.

Smooth riding track is easily secured on tangents or on uniform curves. It is at points of change in curvature that unpleasant shocks and lurches are most liable to occur, and these shocks and lurches, causing discomfort to passengers, are evidences of unprofitable expenditure of motive power, and are damaging to rolling stock and track.

Shocks and lurches, due to changes of curvature, can be prevented on new roads, by constructing the line with transition curves, and on roads already built, by introducing transition curves at points of change. This can be done without disturbing the existing track except near the points of change. The

throw necessary at these points depends on the amount of change in curvature and on the success with which the "eye method" has previously been employed; for no good trackman will line up track to a true circle and tangent. He eases off the change by throwing the track inward from the stakes for a short distance each side of the *P. C.* and the *P. T.* This produces sharper curvature where the modified line joins the line of the stakes in the circular curve and the easement must be very carefully done to avoid making an "elbow."

The transition curve secures this easement at any desired rate of increase in curvature with more uniformity, and distributes the necessary increase of curvature through a longer arc than is practicable through the eye method. It can be applied with equal advantage between tangent and circle, or between arcs of different radii, and with confidence that the result will be an easy riding curve. The series of adjustments so often necessary with the eye method is thus avoided.

The Holbrook spiral was proposed by Mr. Ellis Holbrook, and first used on the Pittsburg, Cincinnati and St. Louis R. R., in 1882. It has since been adopted by the New York and New England R. R., and the New York, Lake Erie and Western R. R.

The distinctive features of this spiral are

1. Uniform rate of increase of curvature with length of arc.
2. Free choice of chord length in locating the curve.
3. Rate of departure from tangent independent of the radius of the connecting arcs.
4. Exact agreement in curvature with connecting arcs at the connecting points.
5. Ready location in either direction from any point of the spiral.

The curve is best defined by the equation

$$n\,D = l. \quad (1)$$

in which $D$ is the degree of the curve in minutes, $l$ the length of the curve in feet, and $n$ a constant determining the rate of increase in curvature.

Let $AB$ in Fig. 1 be an arc of the spiral, whose rate of curvature varies from zero at $A$ to $D$ at $B$. At $B$ the radius is $OB$. Let $OF$ be drawn perpendicular to $AL$, the tangent at $A$, and with the radius $OB$ let the arc $HBCN$ be described. The circular arc $HB$, whose radius equals $R$, is required to turn the

angle secured by the spiral arc $AB$. Referring the spiral to rectangular co-ordinates, whose origin is at $A$ and whose axis of $Y$ is $AE$, if $B$ be any point of the curve, $BE = x$ and $AE = y$. Let $BG$ be drawn tangent to the circular curve at $B$, then $BOH = BGE = i$, the central angle of the spiral arc $AB$.

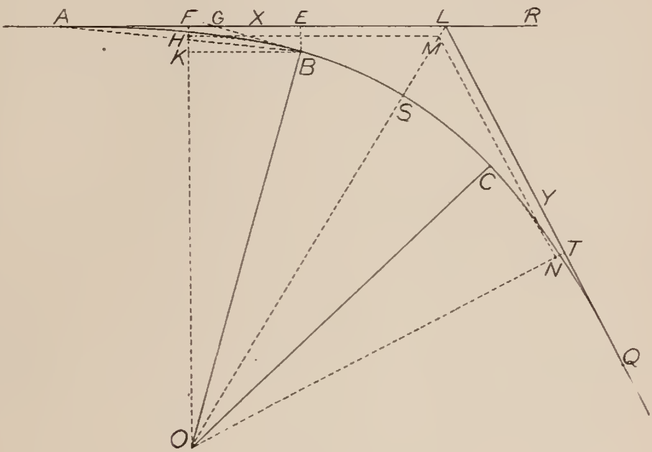


*Fig. 1.*

Denoting the deflection angle $EAB$ by $d$, the back deflection angle from the chord $AB$ is $ABG = i - d$. Also let $AF = y_0$ and $FH = x_0$.

The central angle of an arc of length $\frac{l}{100}$, whose rate of curvature varies uniformly from zero to $D$ is $\frac{1}{2} D \frac{l}{100}$, or substituting the value of $D$ from equation (1)

$$i = \frac{l^2}{200\,n}. \qquad (2)$$

Reducing from angle to arc by multiplying by the length of one minute, $i = \frac{\pi\, l^2}{10{,}800 \times 200\,n}$, or representing the constant factor by $a$ this reduces to $i = a l^2$. The differential equations for $x$ and $y$ in terms of $i$ and $l$, are

$$dx = \sin i.\, dl = \sin a l^2.\, dl,$$
$$dy = \cos i.\, dl = \cos a l^2.\, dl,$$

Expanding $\sin a l^2$ and $\cos a l^2$ by Maclaurin's theorem, and integrating the resulting equations, there follows

$$x = \frac{a l^3}{3} - \frac{a^3 l^7}{42} + \frac{a^5 l^{11}}{1320} - \frac{a^7 l^{15}}{75{,}600} + \text{etc.} \qquad (3)$$

$$y = l - \frac{a^2 l^5}{10} + \frac{a^4 l^9}{216} - \frac{a^6 l^{13}}{9360} + \text{etc.} \quad (4)$$

The deflection angle is $\quad d = tan^{-1} \frac{x}{y} \qquad (5)$

A close approximation to $d$ is obtained as follows: Since $d$ is small, the arc may be substituted for the tangent giving $d = \frac{x}{y}$ and as the series for $x$ and $y$ decrease rapidly, the first term of each will give the ratio with all the precision practically required, whence

$$\frac{x}{y} = \frac{1}{3} al^2, \qquad \text{or} \qquad d = \tfrac{1}{3}\, i. \quad (6)$$

The abscissa $x_o = FH = BE - HK$, but $BE = x$ and $HK = R \; vers \; i$, hence

$$x_o = x - R \; vers \; i. \qquad (7)$$

A close approximation to $x_o$ is obtaiued as follows:

$R = \frac{50}{sin \frac{1}{2} D}$, or approximately, $R = \frac{50}{\frac{1}{2} D} = \frac{100}{D}$, but $i = \frac{1}{2} D \frac{l}{100} = al$, or $D = 200 \; al$, hence $R = \frac{1}{2al}$. Also $vers \; i = 1 - cos \; i = 1 - cos \; al^2 = 1 - \left(1 - \frac{a^2 l^4}{2} + \text{etc.}\right)$, or approximately, $vers \; i = \frac{a^2 l^4}{2}$. Therefore, $R \; vers \; i = \frac{1}{4} al^3$, but since $x$ is very nearly $\frac{1}{3} al^3$, $R \; vers \; i = \frac{3}{4} x$, hence

$$x_o = \tfrac{1}{4} x. \qquad (8)$$

The ordinate $y_o = AF = AE - BK$, but $AE = y$ and $BK = R \; sin \; i$, hence

$$y_o = y - R \; sin \; i. \qquad (9)$$

In combining the spiral with circular arcs the essential points to remember are that the circular arc is computed to join auxiliary tangents distant $x_o$ from the actual tangents and that the *P. S.* (Point Spiral) is $y_o$ beyond where the circular arc joins the auxiliary tangents. Formulas for the most common problems will now be derived.

The simplest case is that of a simple circular arc joining the tangent at each end, through similar spirals as in Fig. 1. The tangent distance $T = AL = QL$. The spiral length $l = AB = CQ$. The arc $BC$ is circular, its radius $OB$ being equal to $R$. The total central angle $\_\_ = QLR = NOH$. The external distance

$E = LS$. The angle $BOH = CON = i$ and $BOC = \triangle - 2i$. It will be noticed that $BC$ produced to $H$ and $N$ joins the auxiliary tangents $MH$ and $MN$, distant $x_o$ from $AL$ and $QL$ at points $H$ and $N$, distant $y_o$ from $A$ and $Q$ respectively; also that if the arc $HN$ be moved outward along $OL$ a distance

$$ML = \frac{FH}{cos\ LOH} = \frac{x_o}{cos\ \frac{1}{2}\triangle},$$

it will join the actual tangents without the aid of spirals. The tangent distance $T = AL = AF + FL$, $AF = y_o$, and

$$FL = OF\ tan\ FOL = (R + x_o)\ tan\ \tfrac{1}{2}\triangle,$$

or, $$T = (R + x_o)\ tan\ \tfrac{1}{2}\triangle + y_o. \qquad (10)$$

The external distance $E = LS = OL - OS$, $OS = R$, and

$$OL = \frac{OF}{cos\ LOF} = \frac{R + x_o}{cos\ \frac{1}{2}\triangle}$$

whence, $$E = \frac{R + x_o}{cos\ \frac{1}{2}\triangle} - R. \qquad (11)$$

From equations (10) and (11) the values of $R$ are found to be

$$R = \frac{T - y_o}{tan\ \frac{1}{2}\triangle} - x_o, \qquad (12)$$

and $$R = \frac{E\ cos\ \frac{1}{2}\triangle - x_o}{1 - cos\ \frac{1}{2}\triangle}. \qquad (13)$$

It is often desirable to use a shorter spiral at one end of the curve than at the other. In this case the spiral arcs $AB$ and $CQ$ in Fig. 1 are unequal, and the auxiliary tangents $MH$ and $MN$ in Figs. 1 and 2 are unequally distant from the actual tangents. Denoting $TQ$ by $y'_o$ and $NT$ by $x'_o$,

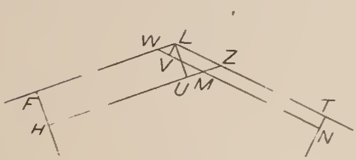


*Fig. 2.*

$$UZ = LU, \quad cot\ Z = x_o\ cot\ \triangle, \qquad LZ = \frac{LU}{sin\ Z} = \frac{x_o}{sin\ \triangle},$$

$$WV = LV\ cot\ Z = x'_o\ cot\ \triangle, \qquad WL = \frac{LV}{sin\ Z} = \frac{x'_o}{sin\ \triangle},$$

and $HM = MN = R\ tan\ \frac{1}{2}\triangle$.

$$T = AL = AF + HM + WL - UZ,$$

or, $$T = y_o + R\ tan\ \tfrac{1}{2}\triangle + \frac{x'_o}{sin\ \triangle} - x_o\ cot\ \triangle, \qquad (14)$$

and $$T' = QL = QT + MN + LZ - WV,$$

or $$T' = y'_o + R\ tan\ \tfrac{1}{2}\triangle + \frac{x_o}{sin\ \triangle} - x'_o\ cot\ \triangle. \qquad (15)$$

The angle $BOH = i$ and $CON = i'$, then $BOC = \Delta - (i + i')$.

With curves 1500 to 4000 feet long, it is inadvisable in re-alignment to attempt to secure a uniform curve, if a better fitting line can be secured by light compounds, say less than 20 minutes. For such a case, or that of any other compound arc, the following method may be used:

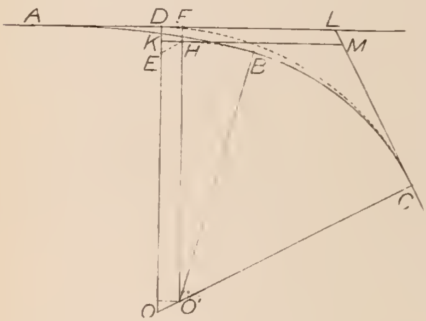


Fig. 3.

Selecting a point $C$, Fig. 3, in the line 400 to 500 feet from the end of the curve and taking deflections to points in the line 300 to 400 feet each side of $C$, the tangent $CL$ is located. The intersection $L$ of $CL$ and $AL$ is found, and the distance $CL$ and the angle $L$ measured. Let $R$ be the radius of the simple arc $CD$ connecting $CL$ and $AL$. With the spiral $AB$ the circular arc $CB$ when produced, must join the auxiliary tangent $HM$ distant $x_0$ from $AL$. The radius $R'$ of an arc to join $HM$ is (see Searles' Field Engineering, Art. 137)

$R' = R - \dfrac{x_0}{vers\ \Delta}$. But $vers\ \Delta = 1 - cos\ \Delta$, $x_0 = x - R\ vers\ i$,

and $vers\ i = 1 - cos\ i$. Making these substitutions and reducing

$$R' = \frac{R\ vers\ \Delta - x}{cos\ i - cos\ \Delta}. \qquad (16)$$

The tangent distance $AL = AD + DL$, $AD = AF - F'D$, $DL = CL$, and $AF = y_0$. Let $HK$ be drawn parallel to $AL$, and $HE$ parallel to $CO$. Then $FD = KH = HE\ sin\ E$, or $FD = (R - R')\ sin\ \Delta$. Hence denoting $AD$ by $d$,

$$d = y_0 - (R - R')\ sin\ \Delta. \qquad (17)$$

Since $AL = CL + d$, the $P.\ S.$ is thus located at $A$. After locating the spiral $AB$, the arc $BC$ is continued, compounding when necessary, to within 400 to 600 feet of the end of the curve, and the intersection with the tangent at that end found. The closing arc is then computed as at the beginning of the curve. If a better fitting arc from $B$ may be secured by a change of three minutes or less in the computed curvature, the change may be made without altering the spiral. Since the

closing arc connects two fixed tangents from a fixed point, the *P. C. C.* on one of them, no deviation from the computed radius is allowable. If the closing arc does not fit satisfactorily, the *P. C. C.* must be changed by changing either the length or radius of the preceding arc. By this method, the introduction of spiral ends affects only the few hundred feet near the ends.

In case there are heavy compounds which should be connected by spirals, the method used will depend on the circumstances. The following will illustrate the general principles of the computations for such cases.

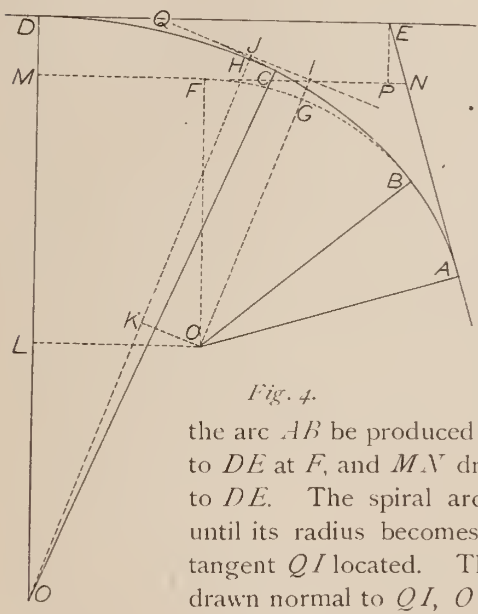


*Fig. 4.*

Let $A$ and $D$, Fig. 4, be two points in a curve which are to be connected by the circular arc $AB$ with radius $R_1$, the spiral $BC$ with radius increasing from $R_1$ to $R_2$ and the circular arc $CD$ with radius $R_2$. The distance $AE$ is to be measured and designated by $T_a$, also $DE = T_d$, and the angle $E = \triangle$. Let the arc $AB$ be produced until it becomes parallel to $DE$ at $F$, and $MN$ drawn through $F$ parallel to $DE$. The spiral arc $BC$ is then produced until its radius becomes infinity at $Q$, and the tangent $QI$ located. The radii $OI$ and $O'J$ are drawn normal to $QI$, $OI$ cutting $AB$ produced at $G$, and $O'J$ cutting $CD$ at $H$. From $O$ a perpendicular is drawn to $O'J$ and $OD$, and $EP$ is made normal to $MN$. Denote $QI$ by $y_1$, $QJ$ by $y_2$, $GI$ by $x_1$, $HJ$ by $x_2$, $IOB$ by $i_1$, and $JO'C$ by $i_2$. Then $OK = y_1 - y_2$; $O'K = O'J - OI = R_2 + x_2 - (R_1 + x_1)$; and $OO'K = \alpha \; tan^{-1} \dfrac{OK}{O'K}$

$$\text{or} \quad \alpha = tan^{-1} = \frac{y_1 - y_2}{(R_2 + x_2) - (R_1 + x_1)} \qquad (18)$$

$$AN = FN = R_1 \, tan \, \tfrac{1}{2} \triangle = T_1; \quad EN = T_a - T_1;$$

$$EP = MD = EN \, sin \triangle = (T_a - T_1) \, sin \triangle,$$

$$NP = EN \, cos \triangle = (T_a - T_1) \, cos \triangle,$$

$$O'L = O'D - LM - MD = R_2 - R_1 - (T_a - T_1)\sin\Delta,$$

$$OL = FM = DE + NP - FN = T_d + (T_a - T_1)\cos\Delta - T_1,$$

$$OO'L = \beta = \tan^{-1}\frac{OL}{O'L}.$$

or $$\beta = \tan^{-1}\frac{T_d + (T_a - T_1)\cos\Delta - T_1}{R_2 - R_1 - (T_a - T_1)\sin\Delta}. \qquad (19)$$

$$DO'C = \phi_2 = OO'L - OO'K + JO'C,$$

or, $$\phi_2 = \beta - \alpha + i_2, \qquad (20)$$

and $$AOB = \phi_1 = \Delta - \beta + \alpha - i_1. \qquad (21)$$

The preceding formulas cover the needs of ordinary practice. Other special problems have been met and solved, but they involve no new principles.

Before taking up the practical application of the preceding theory, I would state that my experience with this spiral has been in re-alignment work only. That experience, however, has convinced me that it is less difficult to locate an easy riding curve than to correct, in re-alignment, the eccentricities of several generations of more or less expert trackmen. It should also be remembered in this connection, that a variation of five feet in the location of a line at any point will rarely have an appreciable effect on the cost of construction, whereas a throw of much over a foot in re-alignment; starts a protest, based on the difficulty of maintaining line and surface, that may extend from the section-foreman to the Superintendent. I am therefore confident that any transition curve successfully meeting the requirements of re-alignment work will be found no less satisfactory in location.

The spiral is used for changes of two degrees or over in curvature. It is located in the field by chords and deflection angles. As the line of the approaches to a curve should be as nearly perfect as possible, the spiral is generally located from the tangent end. When used between a given circle and a heavier or lighter curve, the deflections are obtained by adding to, or subtracting from, the deflections for the given circle those for the same length of spiral. Or, considering any point in the spiral as a point in a circular arc whose radius is that of the spiral at the point taken, the spiral can be located in either direction from that point. The elevation of the outer rail should run from zero at the $P. S.$ to the full elevation required at the

end of the spiral. If, however, in the case of short spirals this would give a rate of rise greater than one inch in thirty feet the elevation should begin back on the tangent.

A set of tables for each spiral required should be prepared for field use. The tables should contain $D$, $l$, $x$, $y_0$ and $d$. Since $x_0 = \frac{1}{4}x$, $i = 3d$, and $i - d = 2d$, their values are readily obtained from $x$ and $d$ and need not be tabulated. The values of $R$ and *nat cos i* may be advantageously added to the tables, and if the spiral is to be located by coordinates, $y$ will also be needed. The number of spirals and extent of tables will depend on the alignment where they are to be used. For ordinary practice $n$ should not be less than 0.5, nor more tnan 1.0, but exceptional cases may require a spiral shorter than would be given by $n = 0.5$. The spiral is named from the length per degree of curvature, thus $n = 0.5$ gives the 30 foot spiral, $n = 1.0$ the 60 foot spiral, etc. Holbrook's tables were for the 30 foot, 60 foot, and 100 foot spirals, computed with $l$ as the independent variable, at intervals of 10 feet up to $D = 8°$. Intermediate values were interpolated when required. We are now using the 30, 40, 50, and 60 foot spirals tabulated at intervals of one foot in length. The functions of the 20 foot spiral are taken from the 40 foot, and those of the 15 foot from the 30 foot by proportion. The following table for the six spirals at $D = 6°$, will illustraie the form we find most convenient, and give an idea of the range they have.

| | $D$ | $R$ | $l$ | $d$ | $x$ | $y_0$ | *cos i.* |
|---|---|---|---|---|---|---|---|
| 60 foot | 6° 00′ | 955.37 | 360.00 | 3° 36′.0 | 22.56 | 179.79 | 0.98229 |
| 50 " | | | 300.00 | 3 00. 0 | 15.68 | 149.82 | 0.98769 |
| 40 " | | | 240.00 | 2 24. 0 | 10.04 | 119.89 | 0.99211 |
| 30 " | | | 180.00 | 1 48. 0 | 5.65 | 89.93 | 0.99556 |
| 20 " | | | 120.00 | 1 12. 0 | 2.52 | 59.98 | 0.99803 |
| 15 " | | | 90.00 | 0 54. 0 | 1.42 | 44.99 | 0.99889 |

It will be noticed that the length of arc for a 6° curve, varies from 90 to 360 feet, $x_0$ varies from 0.36 to 5.64 feet, etc. I would here call attention to the difference between the line of the tangent and circular arc and that between the tangent and spiral. Take the case of a 6° curve traversed by a train running 60 feet per second, or about 41 miles per hour. One second after striking the *P. C.* the car has been carried 1.9 feet from the line of the tangent and is moving at an angle of 3° 36′ to it; in two seconds the figures are 7.2 feet and 7° 12′. Therefore, with such

an alignment, the car and passengers which preserve the same relative position to the car, must receive during the first second sufficient impulse to carry them laterally 1.9 feet, and to rotate them 3° 36′, or in two seconds 7.2 feet and 7° 12′. With the 60 foot spiral the corresponding figures are 0.1 feet and 0° 18′ for the first second, and 0.84 feet and 1° 12′ for the second; or for the 30 foot spiral, 0.21 feet and 0° 36′ for the first second, and 1.68 feet and 2° 24′ for the second. The problem of properly elerating the rail at changes in curvature is easily solved if spirals are used.

One of the standard objections to transition curves is the alleged extra labor and complicated computations necessary to locate them. I shall now give some examples of the application of spirals from the record of our last summer's work on the Delaware Division of the New York, Lake Erie and Western R. R., confining myself chiefly to the difference of the work from re-alignment without spirals. As trials of more than one curve would be as necessary without spirals as with them, to secure the line best adapted to the road bed, I will give only the figures for the satisfactory line. Our curves are numbered from the east end of the Division.

Curve No. 31 furnishes an example of the application of similar spirals at the ends of a simple circular arc. In this case $L$ (see fig. 1) was inaccessible. Points $X$ and $Y$ were taken on $AL$ and $QL$; $XL = 448.54$ feet, $YL = 489.88$ feet, and $L =$ [illegible] $= 70° \ 29'$ were determined by means of a traverse from $X$ to $Y$. A 6° 6′ curve with 30 foot spirals was found satisfactory. $T = (R + x_o) \ tan \ ½$ [illegible] $+ y_o = 736{\cdot}35$, $AB = QC = 183.0$ feet, $i = 5° \ 35'$, $BOC = 70° \ 29' - 11° \ 10' = 59° \ 19'$, and $BC$ is therefore 972.4 feet. The point $A$ was located by measuring $XA = 736.35 - 448.54$ feet, and the point $Q$ by measuring $YQ = 736.35 - 489.88$ feet. The spiral $AB$ was located from $A$ and that of $QC$ from $Q$ by five chords of 30 feet each and one of 33 feet. Then setting the transit at $B$, the vernier was set at $i - d = 3° \ 43½'$ and turned on $A$. The zero reading then gave the line of the tangent at $B$ and $BC$ was located as usual with circular arcs. The measured length $BC$ and deflection to $C$ gave checks on the work. The following is an abstract of the transit notes for stakes every 50 feet on the circle and every 30 feet on the spiral.

| | | DEFLECTION. | ANGLE. | |
|---|---|---|---|---|
| 0 | ⊙ P.S. | 0° 00′ | | |
| 0 + 30 | | 03 | | |
| + 60 | | 12 | | |
| + 90 | | 27 | | |
| 1 + 20 | | 48 | | |
| + 50 | | 1 15 | | |
| + 83 | | 1 51½<br>0 00 | 5° 35′ | Back setting on station 0 = 3° 43½′. |
| 2 + 33 | | 1 31½ | | |
| + 83 | | 3 03 | | |
| * | | * | | |
| 6 + 83 | ⊙ | 15 15 | | Back setting on 1 + 83 = 0° 00′. |
| 7 + 33 | | 16 46½ | | |
| + 83 | | 18 18 | | |
| * | | * | | |
| 11 + 55.4 | ⊙ P.S. | 29 39½<br>1 51½ | 59 19<br>5 35 | |
| + 88.4 | | 1 15 | | |
| 12 + 18.4 | | 0 48 | | |
| + 48.4 | | 27 | | |
| + 78.4 | | 12 | | |
| 13 + 08.4 | | 03 | | |
| + 38.4 | ⊙ P. T. | 00 | | |
| | | | 70° 29′ | |

The additional work necessary in using the spiral was:

1. The addition of $x_0$ to $R$ before multiplying by $tan \frac{1}{2} \Delta$ and the addition of $y_0$ to the product to determine $T$.
2. The subtraction of $2i$ from $\Delta$ before finding the length of the circular arc.
3. The use of two more arcs in locating the curve, and hence two more set-ups for the transit man.

The track was thrown exactly to the stakes, the prescribed elevation given, and the track gang taken to another curve, with no fear of having to come back to re-adjust the approaches to secure an easy riding curve.

Referring to Fig. 1 it will be seen that if a circular arc be replaced by an arc of same radius with spiral ends, the entire curve is moved inward along $OL$ a distance $ML = \dfrac{x_0}{cos \frac{1}{2} \Delta}$. If the external distance be retained, the radius must be shortened to bring the ends of the circular arc $x_0$ withing the actual tangents. In either case the modified line lies entirely within and is shorter than the original line, but if both the radius and external distance be shortened, the line will be thrown outward at the center and inward at the ends, thus giving a minimum change from the original line, and may even be so adjusted as to give exactly the same length of line, thus avoiding the necessity of cutting the rails in throwing the track. We aim, however, to secure the line best fitted to the road bed rather than to the rails.

Curve No. 2 may be taken as an example of a simple arc with unequal spirals at the ends. Referring again to Figs. 1 and 2, the traverse gave $XL = 173.5$ feet, $YL = 163.1$ feet, and $\_ =$ $42° 24\frac{1}{2}'$. To avoid throwing the track on the bridge at the west end of the curve, a 15 foot spiral was used at that end with a $6° 12'$ arc and a 40 foot spiral at the east end.

$x_o = 2.77$, $y_o = 123.87$ feet, $x'_o = 0.41$ feet, $y'_o = 46.47$ feet,

$$HM = R_{6° 12'} \tan \tfrac{1}{2} \_ = 358.85 \text{ feet},$$

$$UZ = x_o \cot \_ = 3.03 \text{ feet}, \quad LZ = \frac{x_o}{\sin \_} = 4.11 \text{ feet}.$$

$$WV = x'_o \cot \_ = 0.47, \quad WL = \frac{x'_o}{\sin \_} = 0.59 \text{ feet}.$$

$$T = 123.87 + 358.85 + 0.59 - 3.03 = 480.28 \text{ feet},$$

$$T' = 46.47 + 358.85 + 4.11 - 0.47 = 408.96 \text{ feet},$$

$$XA = T - 173.5 = 306.78 \text{ feet}, \quad YQ = T' - 163.1 = 245.89 \text{ ft.},$$

$$BOC = \_ - (i + i') = 42° 24\tfrac{1}{2}' - (7° 41' + 2° 53') = 31° 50\tfrac{1}{2}'.$$

$$BC = 513.6 \text{ feet}, \quad AB = 248 \text{ feet}, \text{ and } CQ = 93 \text{ feet}.$$

The computation involves the additional work of finding $UZ$, $LZ$, $WV$, and $WL$, and the additions and subtractions to find $T$ and $T'$. The field work is exactly the same as for curve No 31.

Curve No. 146 will illustrate the application of spiral ends to a compound arc. The distance $CL$, Fig. 3, was found to be 264.05 feet and $L$ was $24° 47'$. $R = T \cot \frac{1}{2} \_ = CL \cot \frac{1}{2} L =$ 1201.81 feet This is very nearly that for a $4° 46'$ curve. Assume that with a 30 foot spiral a $4° 48'$ curve will be required. Then

$$R' = \frac{R \text{ vers } \_ - x}{\cos i - \cos \_} = \frac{1201.81 \text{ vers } 24° 47' - 2.90}{\cos 3° 27\frac{1}{2}' - \cos 24° 47'},$$

$$\text{or} \quad R' = \frac{107.79}{90.28} = 1193.95 \text{ feet}, \quad \text{hence } D' = 4° 48'$$

$$d = y_o - (R - R') \sin \_ = 71.95 - 3.29 = 68.66 \text{ feet},$$

$$\text{and} \quad AL = 264.05 + 68.66 = 332.71 \text{ feet}.$$

This located $A$ and $AB = 144$ feet was run in from $A$. A $4° 50'$ curve was found to fit rather better from $B$ and 500 feet of $4° 50'$ curve was run in, the tangent at the end of the arc located and an intersection with the tangent at the end of the curve found. The closing arc was found to be 615.2 feet of $4° 41.2'$ circle with 281 feet of 60 foot spiral. If the 2 minute compound

at the end of the 144 feet of 30 foot spiral had been considered objectionable, the spiral could have been continued 1 foot farther, giving the exact radius of 4° 50′ circle at the end of the spiral. In this case the spiral ends involved the computation of $R'$ and $d$ and the location of an additional arc at each end of the curve, Referring to Fig. 3 it will be noticed that the introduction of the spiral end throws the curve inward from the *P. C. C*, hence if the preceding arc be so taken as to have the *P. C. C.* lie outward from the existing line, the modified line will lie outward at the *P. C. C.* and inward where the spiral joins the circle, giving a minimum change from the line without spiral ends.

Compound curves requiring spirals between the arcs are usually run in by trial rather than by computing the arcs. With our curves the *P.C.C.*'s and exact degree of the arcs can be found only by trial, and when this is the case, the re-alignment can be as readily completed by trial. A trial will show the location of a *P. C. C.* within 50 feet; then commence at a point back of the *P. C. C.* a distance equal to half the length of the spiral required and run in the spiral to secure the necessary change in curvature, containing the curve from the end of the spiral.

Curve No. 142 contains a 5° arc compounded with a 1° 17.3′ arc. 220 feet of 60 foot spiral was run in from the end of the 5° arc. As the lighter arc was the closing one in the curve, an intersection was made from the end of the spiral, and the degree of the closing arc found to be 1° 17 3′. The difference of 2.7′ in curvature was not considered enough to require the spiral to be extended to secure the exact degree. The following are the deflections to points in the spiral, from the tangent at each end. Since the curvature of the spiral at the lighter end is 1° 20′, the deflections from that end will be those for a 1° 20′ arc added to those for the spiral, while those from the 5° end will be those for a 5° arc less those for the spiral.

| | FROM 5° END. | | | | | FROM 1° 20′ END. | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| STA. | CIRCLE. | | SPIRAL. | | TOTAL. | CIRCLE. | | SPIRAL. | | TOTAL. |
| 0 | 0° 00′ | — | 0° 00′ | = | 0° 00′ | 1° 28′ | + | 1° 20′.7 | = | 2° 48′.7 |
| 0+25 | 0 37½ | — | 0 01 | = | 0 36½ | 1 18 | + | 1 03½ | = | 2 21½ |
| +50 | 1 15 | — | 0 04 | = | 1 11 | 1 08 | + | 0 48 | = | 1 56 |
| +75 | 1 52½ | — | 0 09½ | = | 1 43 | 0 58 | + | 0 38 | = | 1 33 |
| 1+00 | 2 30 | — | 0 16½ | = | 2 13½ | 0 48 | + | 0 24 | = | 1 12 |
| +25 | 3 07½ | — | 0 26 | = | 2 41½ | 0 38 | + | 0 15 | = | 0 53 |
| +50 | 3 45 | — | 0 37½ | = | 3 07½ | 0 28 | + | 0 08 | = | 0 36 |
| +75. | 4 22½ | — | 0 50½ | = | 3 32 | 0 18 | + | 0 03½ | = | 0 21½ |
| 2+00 | 5 00 | — | 1 06½ | = | 3 53½ | 0 08 | + | 0 01 | = | 0 09 |
| +20 | 5 30 | — | 1 20.7 | = | 4 09.3 | 0 00 | + | 0 00 | = | 0 00 |

The central angle of the spiral alone is $3(1^\circ\ 20.'7) = 4^\circ\ 02.'$ and $i - d = 2^\circ\ 41.'3$. The deflections are $2^\circ\ 48.'7 = 5^\circ\ 30' - 2^\circ\ 41.'3$ and $4^\circ\ 09.'3 = 1^\circ\ 28' + 2^\circ\ 41.'3$ as they should be. The central angle of the arc is evidently $4^\circ\ 09.'3 + 2^\circ\ 48.'7 = 6^\circ\ 58'$ and $6^\circ\ 58' = 11^\circ$ (for 220 feet of $5^\circ$ circle) $- 4^\circ\ 02' = 2^\circ\ 56'$ (for 220 feet of $1^\circ\ 20'$ circle) $+ 4^\circ\ 02'$.

When very short spirals are used, the backsight from the *P. C.* to the *P. S.* is also short, and to avoid the error in the angle due to the short backsight, the circular arc may be located from the auxiliary tangent $MH$ in Fig. 1. Locate $H$ at a distance $y_0$ from $A$ and $x_0$ from $AL$, take a backsight on a point along the actual tangent distant $x_0$ from it and locate the arc $HC$ from this auxiliary tangent. The arc $HB$ is not staked out as it is used only to better locate $BC$.

Since track is never laid to a true circle and tangent, the distance $x_0$ is greater than the throw usually required in introducing the spiral. As our re-alignment work is confined to the more irregular curves, our experience does not show the difference of throw required by introducing the spiral, but referring to the values of $x_0$ at $D = 6^\circ$, we find that for a 30 foot spiral $x_0 = 1.41$ feet, and for a 60 foot spiral $x_0 = 5.64$ feet. Hence, for the former spiral the throw cannot exceed 1.41 feet, and for the latter 5.64 feet, and by throwing the circular arc outward at the center, or at the *P. C. C.* in compound curves, these figures may be reduced one-half. We frequently use the 30 foot spiral with less than 0.5 feet throw, and the 60 foot with 0.8 to 1.0 feet throw in the approach to the curve. We have re-aligned very few curves not requiring spirals and I cannot therefore say with confidence how much additional time is required by using the spirals, but I believe 30 minutes per spiral is an ample allowance.

The use of transition curves is increasiug. Improvements in the road bed in other respects make shocks and lurches due to improper changes in curvature more noticable, and the necessity of better methods of easing off these changes more urgent. The continued and extending use of the Holbrook spiral is evidence that it has been found satisfactory where it has been tried. I believe its application will become more extended unless it should be superseded by a better system of transition curves. The preceding methods of applying these spirals are those now used by the writer in re-alignment work. They differ

from those first used by him three years ago, and there seems to be no reason to doubt, that further experience will suggest further extensions and modifications of the methods now used.

E. T. Reisler, '87.

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## EDITORIALS.

Through the kindness of Mr. H. St. L. Coppée, C.E., of the class of '72, the Engineering Society received three photographs showing the method of constructing the submerged spur dikes used in the improvement of the Mississippi River at Greenville, Miss. Two of these views were reproduced in the *Engineering News* of December 14, accompanied by a description of the work.

There is considerable interest manifested at present by Railroad Superintendents and Engineers in the subject of easement or transition curves. The article in the present number by Mr. Reisler, Assistant Engineer, Delaware Division, N Y., L. E. & W. R. R., being the result of several years' experience in the use of the Holbrook spiral, will be a valuable contribution to the discussion concerning the practical value of the various curves which have been proposed for this purpose.

"Roofs and Bridges, Part II. Graphic Statics, by Prof. Mansfield Merriman and Mr. Henry S. Jacoby."

The Journal notes with pleasure the many favorable opinions already expressed by engineers and students of civil engineering outside of Lehigh University concerning this new text-book. It seems to us that one of its valuable features has been that of knowing what to omit. Several new graphical methods are presented for the determination of stresses due to wind strains, to initial tension and to maximum moments and shears under locomotive wheel loads.

The cuts are remarkably clear and distinct. The solving of many problems showing the application of the different principles to numerous structures, together with tabulated results, will show at once the most approved methods of solution and the construction of suitable tables. We extend our congratulations to the authors, believing that the work will be a success.

L. P. B.

## ALUMNI NOTES.

1878.

M. P. Paret, C.E., is U. S. resident engineer at Savannah. Ga.

1884.

—Richard W. Walker, C.E., who is an engineer on the Boundary Survey between Guatemala and Mexico, is spending his vacation at Glen Moore, Chester Co., Pa.

1887.

—M. D. Pratt, C.E., has returned to the East and resumed the position which he formerly occupied with the Johnson Steel Street Rail Co., Johnstown, Pa.

—Alexander Bonnot, C.E., is at the Laclede Gas Works, Main and Howard Streets, St. Louis, Mo.

1888.

—M. L. Byers, C.E., was declared elected as Junior member of the American Society of Civil Engineers at the January meeting, 1890.

—C. E. Butler, C.E., of the firm of Fehr & Butler, is engaged in general engineering work at Easton, Pa.

1889.

—Pearce Atkinson, M.E., is engaged in the construction of Union Pacific R. R. new lines in Utah. Headquarters, Salt Lake City.

—L. C. Taylor, C.E., is assistant to the National Astronomer of the Argentine Republic located at Buenos Ayres.

—Twenty-four members of the class of 'Eighty-eight, and twenty-six of 'Eighty-nine, have become members of the Alumni Association.